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FURTHER STUDIES OF THE BEHAVIOR OF THE PACIFIC SARDINE (SARDINOPS CAERULEA) IN AN ELECTRICAL FIELD

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The first stage of experimental studies on galvanotropic responses of the Pacific sardine (*Sardinops caerulea*), using pulsating direct current of low frequencies and a triangular wave form, was described by Groody, Loukashkin, and Grant (1952). That account was concluded (pages 317–322) by a study of the effects of the three variables involved, namely, maximum current density, ratio of current-on to current-off periods, and frequency of pulsation. During this experiment, 900 tests were made.

Methods

The experimental tank and electrical design used in the present study are shown in figure 1 (after Groody, *et al.*, 1952, p. 312).

The following definitions, adopted in the earlier report (*op. cit.*), were used.

Perfect. When all four fish responded readily to each reversal of the poles and displayed a directional reaction toward the positive pole.

Good. When three of the four fish displayed the reaction given above or when all four fish failed to respond to one of the three reversals of poles.

Fair. When two of the fish readily responded to all pole reversals, or when all fish responded to at least one reversal.

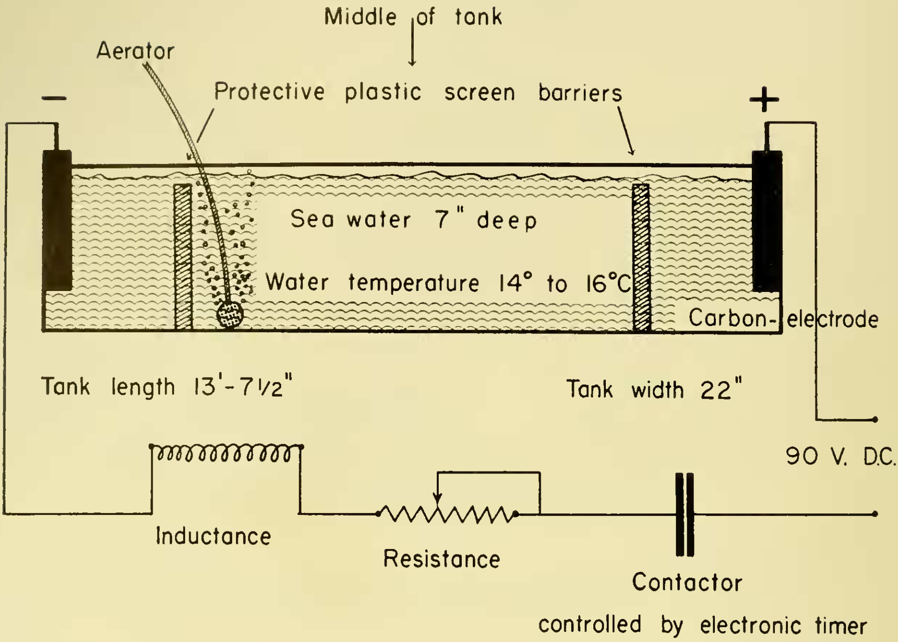


Figure 1. Diagram of experimental wooden tank and electrical circuit for triangular wave form of pulsating direct current. Reversing switch not shown (after Groody, Loukashkin, and Grant, 1952).

None. When one or none of the fish displayed directional reactions.

The first two grades were classified as *satisfactory* and the last two grades as *unsatisfactory* (table 1).

In addition to the above definitions for recording behavior, records were made of the fishes' response to the current relative to fright reactions to stimuli and to apparent control of their own swimming movements. For these records, the following symbols were used:

(—). Swimming movements apparently under control of the fish, no directional response, and all reactions to fright stimuli retained.

(½+). The avoidance reaction to the barrier was retained, but the fish did not respond to vibrations of the tank with fright reactions.

(+). Directional responses apparently controlled by electrical current density only. Normal fright reactions to the barrier or to other stimuli completely lost.

(+ +). In addition to the reactions above under (+), the fish remained in contact with the protective screen next the positive pole as

TABLE 1

Sardine reactions to variations in maximum current density of the square wave form direct current pulsating at low frequencies. (180 observations for each of the five densities tested.)

Maximum current density in milliamperes	*Directional swimming Results in per cent*							*Control of movements Results in per cent*						
	Unsatisfactory			*Satisfactory*				*Unsatisfactory*			*Satisfactory*			
	None	*Fair*	*Both*	*Good*	*Perfect*	*Both*	*Total*	(—)	(½+)	*Both*	(+)	(++)	*Both*	*Total*
10	35.5	40.0	75.5	19.0	5.5	24.5	100.0	53.3	44.5	97.8	2.2	0	2.2	100.0
15	25.6	41.1	66.7	25.5	7.8	33.3	100.0	35.5	37.8	73.3	24.4	2.3	26.7	100.0
20	14.4	27.8	42.2	37.8	20.0	57.8	100.0	21.1	15.6	36.7	41.1	22.2	63.3	100.0
25	20.0	27.8	47.8	24.4	27.8	52.2	100.0	16.7	11.1	27.8	30.0	42.2	72.2	100.0
30	11.1	17.8	28.9	33.3	37.8	71.1	100.0	8.9	13.3	22.2	15.6	62.2	77.8	100.0

TABLE 2

Sardine reactions to variations in ratio of current-on to current-off periods of the square wave direct current pulsating at low frequencies. (180 observations for each of the five ratios tested.)

Ratio of "on" to "off" periods	*Directional swimming Results in per cent*							*Control of movements Results in per cent*						
	Unsatisfactory			*Satisfactory*				*Unsatisfactory*			*Satisfactory*			
	None	*Fair*	*Both*	*Good*	*Perfect*	*Both*	*Total*	(—)	(½+)	*Both*	(+)	(++)	*Both*	*Total*
1 : 3	60.0	34.4	94.4	4.4	1.2	5.6	100.0	65.6	21.1	86.7	10.0	3.3	13.3	100.0
1 : 2	27.8	43.3	71.1	20.0	8.9	28.9	100.0	38.9	26.7	65.6	20.0	14.4	34.4	100.0
1 : 1	11.1	35.6	46.7	43.3	10.0	53.3	100.0	20.0	22.2	42.2	31.1	26.7	57.8	100.0
2 : 1	4.4	30.0	34.4	35.6	30.0	65.6	100.0	4.4	33.3	37.7	30.0	32.3	62.3	100.0
3 : 1	3.3	11.1	14.4	33.3	52.3	85.6	100.0	6.6	19.0	25.6	22.2	52.2	74.4	100.0

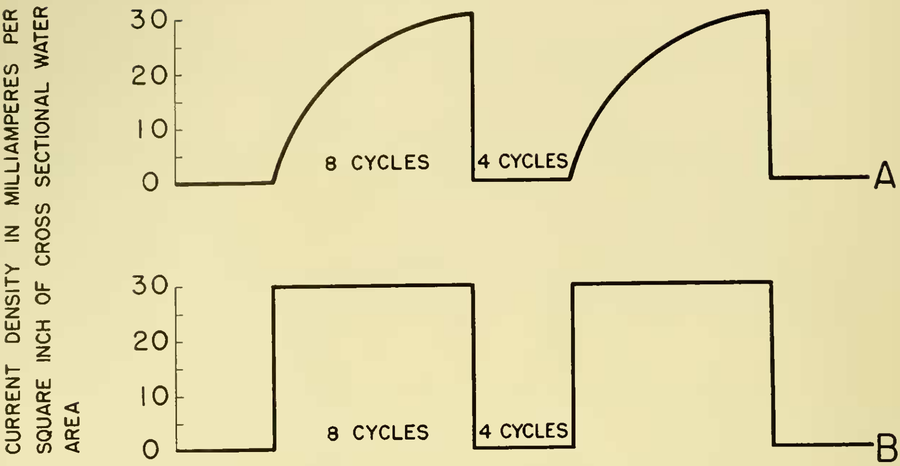


Figure 2. Triangular and square wave forms of direct current pulsating at low frequencies with a pulse of 30 milliamperes of maximum current density and an "on" to "off" ratio of 2:1. The frequency of pulsation is 5 per second. Timing base is 60 cycles per second.

long as the current was on. This was, of course, the most pronounced reaction to the current short of stunning and death.

(—) and (½+) were classified as *unsatisfactory*, (+) and (++) as *satisfactory* (table 2).

RESULTS

The present studies centered on the stimulating effects on sardine behavior of: (1) the square wave form of direct current pulsating at low frequencies; (2) application of higher frequencies of pulsating direct current using triangular and square wave forms; (3) application of half-wave rectified 60-cycle alternating current; (4) application of quarter-wave rectified 60-cycle alternating current; and (5) application of the condenser discharge impulse.

(1) *Effects of the square wave form of direct current pulsating at low frequencies.* Using the same facilities and equipment and following the same procedure and recording as described in the preliminary report cited above, a series of 900 analogous tests were made in order to investigate the effects of the square wave form of direct current pulsating at low frequencies.

The square wave impulse was obtained by omitting an inductance from the circuit diagrammed in figure 1. Contrary to the triangular

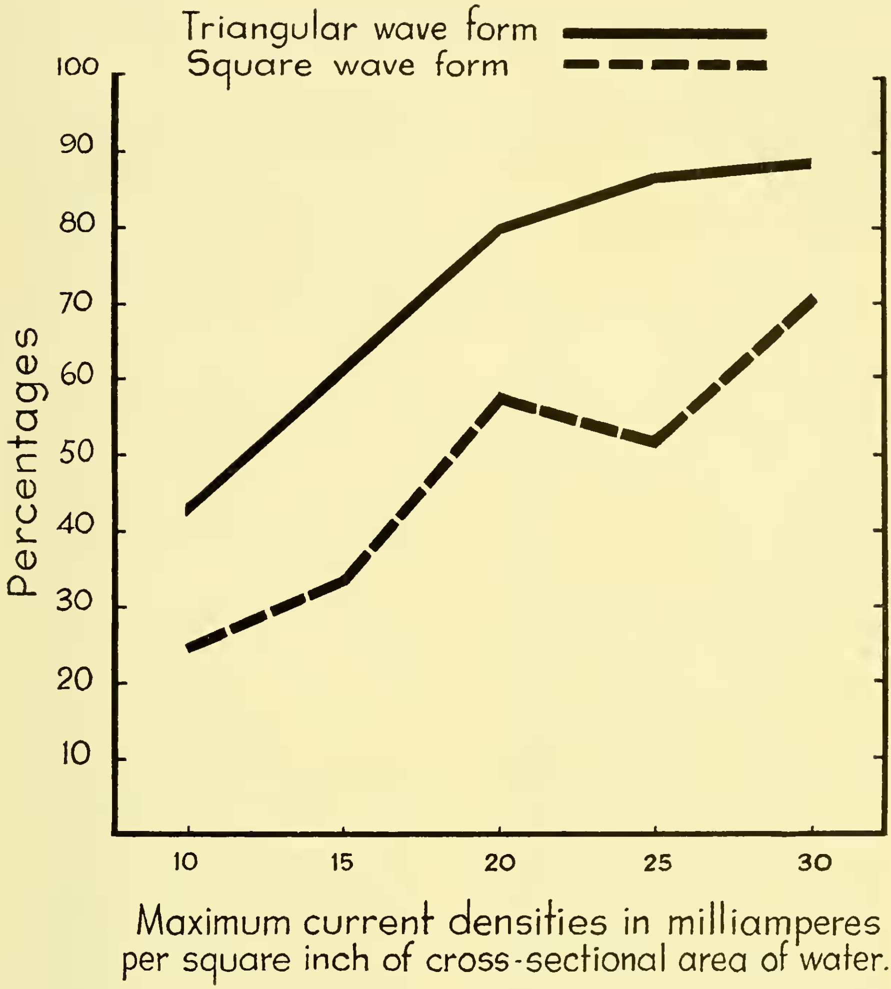


Figure 3. "Satisfactory" directional reactions (in per cent) of the sardines in an electrical field produced by using triangular and square wave forms of direct current pulsating at low frequencies. Percentages are based on 180 observations for each of the five maximum current densities of each wave form tested.

wave form, the square wave impulse rises instantly to its maximum, maintains this density for the desired period and then, like the triangular wave, it returns abruptly to zero (figure 2). The results of these tests are shown in tables 1 and 2.

The tests indicate that current density is the most critical factor. When the maximum current density increases from 10 to 30 milliamperes per square inch of cross-sectional area of water, there is a well-displayed trend toward increase of "satisfactory" results. As is shown in figures 2 and 3, this is true of both wave forms but is more marked in the triangular wave.

A comparative analysis of the results obtained indicates that the triangular wave form produced comparatively better directional responses than did the square wave, while "satisfactory" control of fish movements was obtained more frequently with the square wave. However, the difference does not appear to be significant. It can be concluded that both wave forms of direct current pulsating at low frequencies* are "satisfactory" in producing a directional response and in control of the sardine movements.

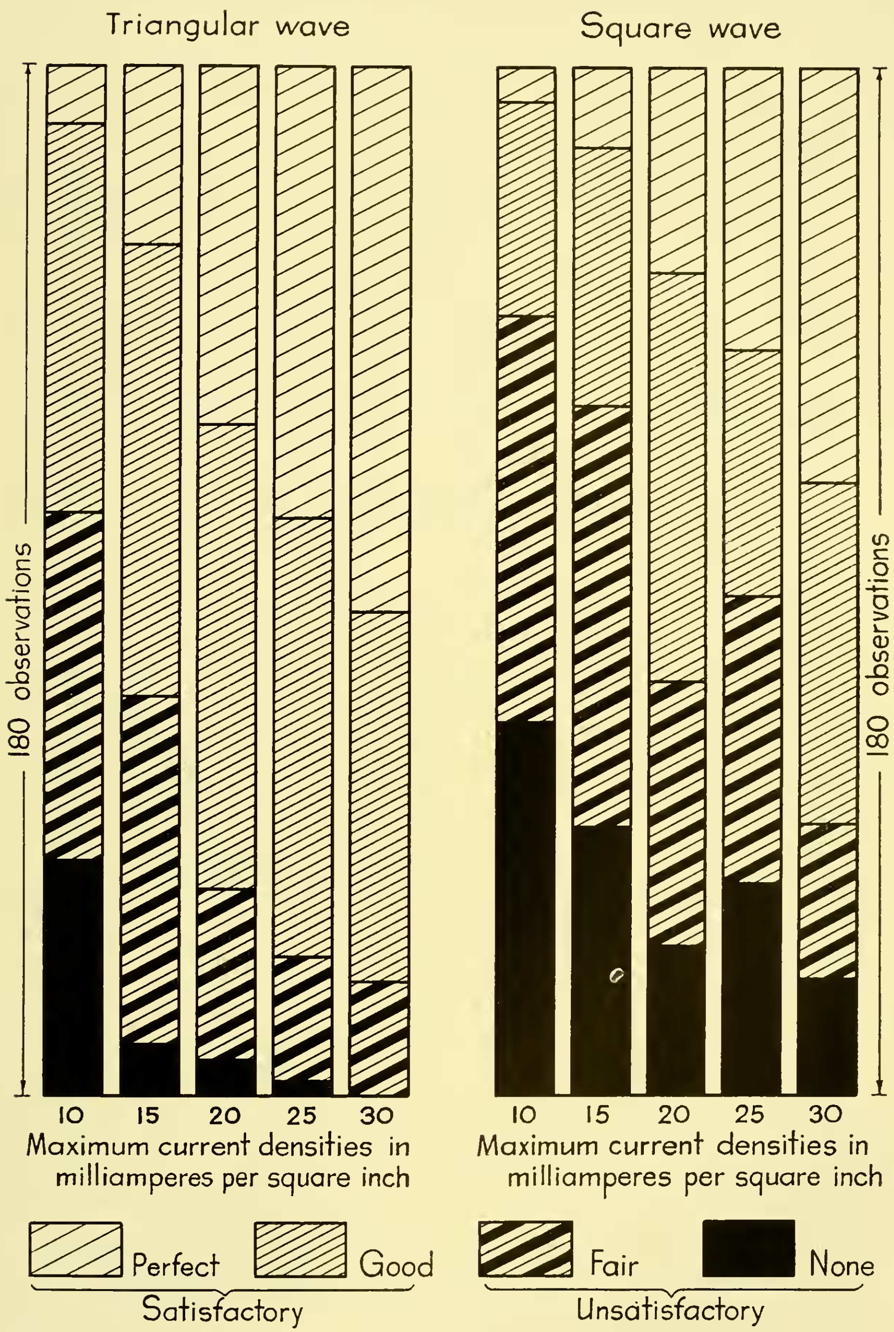
(2) *The application of higher frequencies of pulsating direct current using triangular and square wave forms.* In order to obtain pulsating direct current of the higher frequencies, a high-speed mechanical interrupter was introduced into the circuit diagrammed in figure 1. Using both types of current wave forms and applying a 1:1 ratio of current-on to current-off periods (figure 5: A and B), the following frequencies were tested: 5, 20, 35, 50, 65, and 80 per second.

The experiments disclosed that the *average current density* of pulsating direct current is a more important factor in producing directional swimming and control of fish movement than the *maximum or peak current density.* Also, it was found more convenient to express current density as an average value since this can be read directly from the ammeter dial. This average value is dependent on the ratio of the "on" to "off" periods.** For example, using a square wave form and an "on" to "off" ratio of 1:1, the average current density would be one half of the maximum or peak current value attained during the "on" period. Applying the same value of the maximum current density and changing the "on" to "off" ratio from 1:1 to 2:1 and 1:2, the average current density will be higher when a 2:1 ratio is used, lower when a 1:2 ratio is used. This statement differs from, but is not inconsistent

*The table of sardine reactions to variations in current pulsation frequency is omitted because the rate of current pulsation (within the range of 2, 4, and 6 times per second) seemed to have no significant effect on directional swimming and control of fish movements. This observation is in full accord with the records for the triangular wave form given in the preliminary report (Groody, *et al.*, 1952, table 2).

**When straight direct current (i.e., not pulsating) is used, the values of maximum and average current densities are equal.

Figure 4. Numbers of classified directional reactions of the sardines per current density tested using triangular and square wave forms of direct current pulsating at low frequencies. Each column for each maximum current density represents 180 observations.


Triangular wave
Square wave
180 observations
180 observations
10
15
20
25
30
Maximum current densities in milliamperes per square inch
10
15
20
25
30
Maximum current densities in milliamperes per square inch
Perfect
Good
Satisfactory
Fair
None
Unsatisfactory

with, that in our earlier paper (Groody, *et al.*, 1952, p. 318, and table 3). It was shown there that control of movement was increasingly successful with increasing ratio of current-on to current-off periods. It will be obvious that this result is satisfactorily explained as an increase in *average current density.*

Using a triangular or any other wave form and applying the same values of the maximum or peak current density and the same ratios of the "on" to "off" periods, the average current density would be always less than that of the square wave form.

Use of the higher frequencies in this experiment produced "perfect" directional swimming and full (+ +) control of fish movements at considerably reduced average current densities. The current density required to produce highly "satisfactory" results at a frequency of 65 to 80 pulses per second was only 50 per cent of that needed at a frequency of five pulses per second.

Optimal ranges of the average current density established by the above experiments for the Pacific sardine 200–300 mm. in standard length are shown in table 3.

TABLE 3

The Effect of Frequency of Pulsation Upon Optimal Average Current Density
(210 Observations)

Values of frequencies of pulsating direct current, using square or triangular wave forms and 1:1 ratio of current-on to current-off periods.	Values of the optimal average current densities which produce "perfect" directional swimming and full (+ +) control of fish movements.
5 times per second	From 8 to 12 milliamperes/sq. inch
20 " " "	" 8 to 10 " " "
35 " " "	" 6 to 8 " " "
50 " " "	" 6 to 8 " " "
65 " " "	" 4 to 6 " " "
80 " " "	" 4 to 6 " " "

(3) *The application of half-wave rectified 60-cycle alternating current.* As frequencies of pulsating direct current as high as 65 to 80 per second were found to be more effective than the low frequencies, in regard to reducing the amount of average current density required to produce directional swimming and control of fish movements, it was then decided to test the sardines in an electrical field of half-wave rectified 60-cycle alternating current, using a standard mercury vapor rectifier tube. This produces a rounded and evenly sloped current wave form with a 1:1 ratio of current-on to current-off (figure 5C).

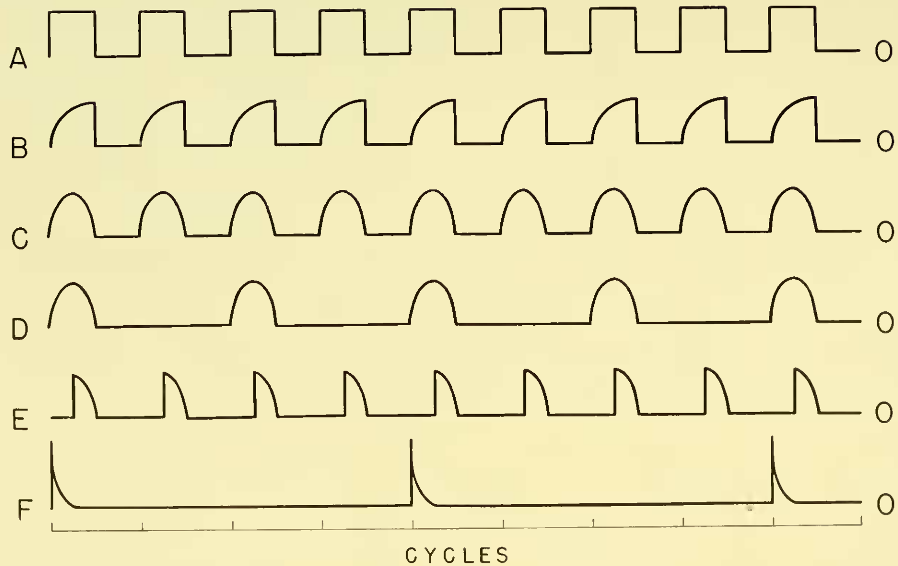


Figure 5. The wave forms of pulsating current with timing base of 60 cycles per second: A. The square wave form of direct current pulsating 60 times per second with an "on" to "off" ratio of 1:1; B. The triangular wave form of direct current pulsating 60 times per second with an "on" to "off" ratio of 1:1; C. The half-wave rectified 60-cycle alternating current; D. The same half-wave rectified 60-cycle alternating current interrupted 30 times a second; E. The quarter-wave rectified 60-cycle alternating current; F. Condenser discharge impulse at a frequency of 14 to 15 times per second.

Each cycle—1/60 of a second.

Using the facilities and equipment shown in figure 1 with the exception that the inductance and contactor were left out of the circuit, a series of more than 300 tests were made, using groups of four sardines 200–230 mm. in standard length, the procedure and recording being the same as in previous experiments.

From these experiments it was found that the optimal average current density required to produce "perfect" directional swimming and fully controlled fish movements varied within the range of 3.3 to 5.0 milliamperes per square inch of cross-sectional area of water. The higher average current densities from 6 to 9 milliamperes showed a tendency to stun the fish and it appears that this stunning effect is directly related to the increase in average current density.

Following the experiments with the sardines, topsmelt (*Atherinops affinis*), 100–110 mm. in standard length, were subjected in groups of four to the stimulation. They were found to respond in a similar manner to the sardines, the only difference being that the optimal average current density requirement was found to be almost twice as high (table 4). This is in accord with a statement made in the earlier study (Groody, *et al.*, 1952, p. 317) concerning the apparent inverse relationship between the amount of current density needed to produce directional swimming and the size of the fish. It should be pointed out, however, that these observations were made on different species of fish. Unfortunately, the species of fish used were available in only one size. Interestingly, McMillan (1929, p. 102), who studied the effect of voltage gradient required to produce paralysis on rainbow trout (*Salmo irideus*) and chinook salmon (*Oncorhynchus tschawytscha*) that varied in length from 1.87 to 12.50 and from 3.10 to 31.75 inches respectively, states ". . . the voltage gradient required to produce paralysis is inversely proportional to the length of the fish. In other words, the long fish require a much lower field strength to paralyze them than the short ones."

Further, to check this relationship between length of fish and current density required, jacksmelt (*Atherinopsis californiensis*) 300–330 mm. in standard length, were similarly tested in groups of four. This fish, too, reacted as did the sardines but the optimal average current density requirement was as low as 2.5 to 3 milliamperes per square inch of cross-sectional area of water. Higher current density caused the fish to roll over and remain stunned until the current was turned off.

In each of the three species tested with average current densities above the optimal range, fish have been stunned to various degrees but all recovered as soon as the current was turned off. When returned to their holding tanks, the fish rejoined schools and apparently suffered no ill effects from the experiments.

In the case of all three species of fish, the half-wave rectified 60-cycle alternating current caused a higher speed of swimming than the triangular or the square forms. Other observations indicated that, under the influence of the half-wave rectified A.C., the fish reacted with considerably more ease and showed less distress during forced swimming toward the positive pole. This is not easy to establish on a quantitative basis, but was a fact of observation that was confirmed by several observers.

Typical behavior of the fish in a field of half-wave rectified 60-cycle A.C. is summarized in table 4.

TABLE 4

Reactions and Optimal Average Current Densities Using Half-Wave Rectified 60-cycle Alternating Current

Species of Fish Stimulated	Standard Length of the Fish Tested in Millimeters	Optimal Range of the Average Current Density Required to Produce "Satisfactory" reactions as Described in the Lower Part of This Table
Pacific Sardine *Sardinops caerulea*	200 – 230	3.3 to 5 milliamperes
Topsmelt *Atherinops affinis*	100 – 110	7.0 to 9.0 "
Jacksmelt *Atherinopsis californiensis*	300 – 330	2.5 to 3.0 "

Description of fish behavior in an electrical field within the optimal range of the average current densities:

Orientation instantaneous and simultaneous. Directional swimming "perfect"; response to reversals of polarity immediate and coordinated. Control of movement full (+ +): fish cannot avoid barrier inserted between swimming fish and positive pole; all natural fright reactions to disturbing stimuli entirely lost; upon reaching protective screen (two feet in front of the positive electrode) fish cannot swim away, being strongly attracted toward the electrode. Swimming very rapid, sometimes performed as a rapid gliding over the water surface toward positive pole. Easy on fish.

This half-wave rectified 60-cycle alternating current was also interrupted 30 times a second by using a thyratron tube, and the wave form so obtained is shown in figure 5D.

The experiments carried out on the same three species of fish resulted in obtaining "perfect" directional swimming and fully controlled movement (+ +) of the fish as described above, however, the amount of the average current density required to produce these reactions was about one-half of that established for the pure (uninterrupted) half-wave rectified 60-cycle alternating current.

(4) *The application of the quarter-wave rectified 60-cycle alternating current.* For experiments using a wave form that starts with the maximum current and slopes gradually to zero as shown in figure 5E, the authors used a mercury vapor thyratron tube and phase-changing equipment. It is actually a quarter-wave impulse and the reverse of the originally tested triangular wave form of pulsating direct current.

Use of this quarter-wave form and the same optimal range of the average current densities and species of fish as in the experiments with half-wave rectified 60-cycle A.C. (table 4), resulted in fish reactions that were less satisfactory. In this experiment, over 200 tests were made. Although the fish did orient and swim toward the positive pole, their direction of swimming being fully under electrical control, it was obvious that they experienced certain difficulties and attempted to escape from the field by raising their heads out of water and trying to jump over the sides of the tank. There were several cases of strong stunning effects, even when the lower values of the optimal range of the average current density were applied. It also required a longer period for the fish to relax and resume normal behavior after these tests than it did after any of the previous experiments. These effects were observed in the responses of each of the three species used.

It is assumed that in order to obtain an optimal range of the average densities established for the half-wave current, the magnitude of the wave peak must be much greater in the quarter-wave impulse than in the former. In all probability, this is the cause of a strong and lasting stunning effect observed on the fish tested.

(5) *The application of the condenser discharge impulse.* The present investigations of the effects of various wave forms and frequencies of pulsating direct current were completed by experiments with condenser discharge pulses having a frequency of approximately 14 per second. This was produced by charging a 50 MF condenser from a source of half-wave rectified 120-volt alternating current and discharging through a mercury vapor thyratron tube. The wave form thus obtained is diagrammed in figure 5F.

A series of more than 300 tests showed that this type of current impulse was also effective in producing directional swimming of the sardine. The optimal range of the average current densities was found to be as low as 0.4 to 0.8 milliampere per square inch of cross-sectional area of water.* It is evident from these tests that the amount of electrical

*The negative results of the effects of the condenser discharge mentioned in the preliminary report (Groody, *et al.*, 1952) were probably due to the discharge of condenser through mechanical contactor instead of the thyratron tube.

energy required to produce directional swimming of the sardine is much less using condenser discharge than by employing other wave forms tested.

When optimal average current densities were used the sardines' reactions showed that while forced directional swimming was clearly displayed, the fish experienced considerable difficulty in reorienting when the polarity of the electrical field was reversed. They usually continued swimming in the original direction for a short distance. It was observed that while they were attempting to turn, their bodies vibrated at what appeared to be the pulse frequency. It also appeared that this type of current impulse caused the fish to become exhausted in a short time: they were easily picked up by hand for transferring in a bucket back to their holding tank.

Similar effects were observed with jacksmelt. Their optimal range was found to be between 0.4 to 0.6 milliampere per square inch. No topsmelt were available at the time of the experiments.

Although controlled directional swimming was clearly displayed, the full control of fish movements (+ +) was not immediately obtained: both the sardine and jacksmelt were able to leave the positive pole and swim away toward the negative pole; however, after several such escaping attempts the fish finally returned to the positive pole.

Application of the higher values of the average current density above optimal range in order to produce an immediate and full control of the fish movements resulted in a strong stunning effect on the fish as soon as the current was turned on. One of the sardines used in these tests became totally blind, and it died 12 hours later.

The saving in current obtained by the use of condenser discharge is particularly significant in view of the fact that one of the most important problems in the development of electrofishing is the large amount of power needed to establish suitable current densities in sea water.

DISCUSSION

Observations made during the course of experimental studies of the behavior of the Pacific sardine carried on in the California Academy of Sciences since 1950, have established that this species is highly susceptible to stimulation by electrical currents. The fish usually begin to feel the presence of an electrical field even when the lowest values of average current density are applied.

The sensitivity of the sardine to changes in average current density and the degree of stimulating effect that has been once established for each density value remain constant. This is true for each particular type of pulsating current tested. As soon as the optimal range of average current density required to produce directional swimming and control of fish movement has been found, the sardine's reactions will always remain identical regardless of the number of times the tests are repeated or the sequence of the tests.

The observations present another fact, namely, the sardines just captured or the ones that have been kept in captivity for an extended period of time display identical sensitivity as described above. No conditioning has ever been observed despite the fact that the experimental fish were confined in the Steinhart Aquarium's holding tanks for more than two and one-half years and were used twice a week on the average in electrical stimulation experiments. In contrast to the topsmelt and jacksmelt, their peculiar reactions to each particular value of the average current density applied, have been invariably the same. Topsmelt and jacksmelt usually became conditioned after 5–10 successive stimulations, and therefore in the experiments here reported these fishes have often been replaced by the fresh specimens not previously subjected to the electrical field.

The results of the effects of various wave forms and currents and of different frequencies recorded during the course of experimental studies have been checked many times. These repeated tests have proved that the optimal ranges of average current density experimentally determined for the three species of fish for each different type of electrical current, have always remained essentially the same.

The observations also indicate that, when a proper value of average current density is applied and the fish movements are fully (+ +) controlled, their natural fright reactions to disturbing stimuli are entirely suppressed and the fish can be easily picked up by hand. This observation applies to all three species used in the present investigations.

Conclusions

1. The five types of pulsating direct current wave forms used by the experimenters are effective in producing forced directional swimming of the Pacific sardine (*Sardinops caerulea*) and also the jacksmelt (*Atherinopsis californiensis*), and the topsmelt (*Atherinops affinis*) that were used as controls.

2. All wave forms tested can produce full (+ +) control of fish movements and force them to the positive pole where they can be held until the current is turned off.

3. The electrically stimulated reactions can be obtained and will remain constant if a proper optimal range of average current density is determined for each particular species and size.

4. Current density is the most critical factor in producing forced directional swimming and control of fish movements.

5. Average current densities above the optimal range may cause temporary paralysis or even death of the fish whereas those below produce a slight directional response or none at all.

6. The optimal average current density required to produce "satisfactory" directional swimming and controlled (+ +) movement of fish appears to vary inversely with the size of the fish.

7. Full control of fish movement and forced directional swimming can be obtained with any frequency of current pulsation from 2 to 80 per second; the frequencies above 80, however, have not been tested.

8. The use of a pulse frequency as high as 60 to 80 per second reduced the optimal average current density to 50 per cent of the amount required at a frequency of 5 per second.

9. The most effective and "satisfactory" results, as far as the smoothness of performance and school coordination are concerned, were recorded when either continuous or interrupted half-wave rectified 60-cycle alternating current was used.

10. Condenser discharge pulse produced the "satisfactory" reactions at very low average current densities (0.4 to 0.8 milliampere). This represents a substantial decrease in power requirements.

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